PREPARATIONS FOR THE AIRBORNE ATV-5 RE-ENTRY OBSERVATION CAMPAIGN

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Abstract:

Preparations are presented that were made to conduct an airborne observation campaign to monitor the planned shallow re-entry of the final Automated Transfer Vehicle ATV-5 "Georges Lemaitre" in early 2015. The campaign was to provide physical data to validate re-entry simulation tools to be used for the future International Space Station de-orbit and shallow uncontrolled reentries. The campaign was a joint NASA/ESA initiative. This manuscript presents the issues of campaign coordination and logistics, the three science goals - explosion analysis, fragment identification and fragment tracking, and the re-entry predictions using the SCARAB software. The achievable level of measurement detail is discussed. The re-entry was planned for February 27th, but had to be cancelled on February 10 due to problems onboard the ATV-5 vehicle. The work presented here provides information that can benefit a future observation opportunity of a controlled shallow spacecraft re-entry.

Introduction:

On-ground safety considerations for re-entry are nowadays a required aspect of the design phase of any spacecraft that will re-enter the Earth's atmosphere at the end of its operational lifetime. In the case of a large structure such as an Earth observation satellite, the International Space Station's (ISS) re-supply spacecraft, or the space station itself, the break-up scenario is difficult to predict. This is predominantly because the processes driving the vehicle fragmentation are not sufficiently understood and the break-up is strongly dependent on the flight trajectory during re-entry.

Various re-entry simulation tools have been developed since the 1990s in order to assess destructive re-entry and its impact with respect to on-ground safety. In Europe, the SCARAB (Spacecraft Atmospheric Re-Entry and Aerothermal Break-up) software is one of the most advanced tools for these simulations. SCARAB was used to study the end-of-life destructive re-entries of ESA's Automated Transfer Vehicle (ATV), an International Space Station (ISS) resupply spacecraft [1].

To validate the SCARAB model, the norminal re-entry of the first ATV-1 "Jules Verne" was observed from aboard the NASA DC-8 in 2008 [2,3]. Here, the focus was the comparison of the nominal entry trajectory breakup with the predicted fragmentation behaviour.

To further validate the model, it was planned to have the final ATV-5 "Georges Lemaître" reenter the atmosphere along a modified shallow re-entry trajectory. This trajectory was chosen as a simulation scenario of the re-entry of the ISS at some time in the future. It also served to better predict the breakup of future uncontrolled reentries.

The re-entry was planned for February 27th, around 12 UT, thirteen days after undock from ISS so that the re-entry could be observed in night time conditions. NASA's DC-8 Airborne Laboratory was again deployed to host an international observation team with a wide array of instruments.

Unfortunately, one of ATV-5's batteries failed on February 3, removing the redundancy of a number of ATV-5's subsystems. Because ATV-5 now had to be re-entered immediately after undock, this led to the decision on February 10 to cancel the ATV-5 reentry observation campaign [4]. On the day of that decision, the DC-8 observing campaign finished its flight readiness and operational readiness reviews.

Because the preparations up to that point serve future campaigns that study shallow reentries, this paper presents the design of the ATV-5 observation campaign, aspects of mission planning and the prediction tool developed to assist with mission planning.

ATV-5:

The ATVs were a family of 5 spacecraft developed and built in Europe mainly by Airbus DS. The main purpose was to transport experiments and goods to the ISS.

The ATV spacecraft is divided in three parts, the pressurized experiment module, the avionics bay and the propulsion bay (see Fig. 1).

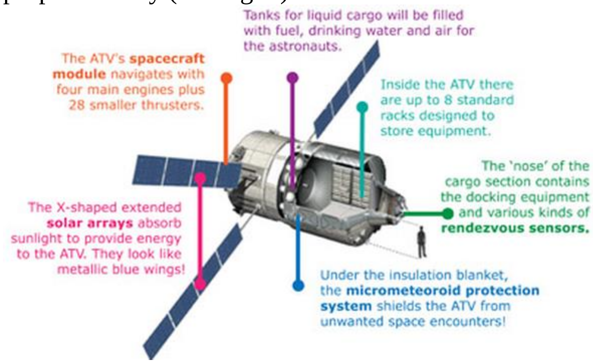

Fig. 1: The ATV spacecraft has three main parts: the spacecraft module, the avionics part and the pressurized experimental module.

ATV-5 was the heaviest payload (20t) launched thus far with an Ariane 5 rocket. When it undocked from the ISS on February 14th, its mass still was 13t due to waste products being discarded [4]. The large mass, well understood design, combined with the earlier observing campaign for ATV-1, made it an ideal platform for re-entry studies.

The re-entry was planned for the 27th of February 2015 at around 12:00UT over the South Pacific Ocean Uninhabited Area (SPOUA) in order to provide night-time viewing conditions for observations from the DC8 platform and from the ISS itself. Two breakup recorders were also deployed on ATV-5 to document processes during the reentry, the European Break Up Camera (BUC) and the Re-entry Breakup Recorder (REBR) from Aerospace Corporation. BUC was developed by a consortium of RUAG, ETH Zürich, and Viasat from Switzerland, the German Aerospace Center in Stuttgart, Germany, and Denmark's GomSpace [5]. It consists of a heat shield protected ellipsoid containing a camera and different sensors measuring attitude and g-forces as well as temperature and rotation. The information is transmitted via Iridium satellite communication after the hot phase of the re-entry and prior to splash down in the Pacific Ocean. REBR contains several sensors for internal temperatures and pressures, a GPS module for real-time location information and a satellite modem for data transmission and communication [6]. While the REBR was unmounted from ATV-5 when the shallow re-entry was cancelled, the BUC was onboard ATV-5 during its re-entry into the Earth's atmosphere. However, due to communication issues, only the fact that almost 6000 images and sensor data from accelerometers and magnetometers were recorded could be confirmed, but the actual data was lost [4].

To meet the entry date in early February, the docking phase had to be extended by two months, with undocking scheduled for February 14th. Because a Progress transporter was scheduled to arrive in early February 2015, a free flight phase of about 13 days was foreseen.

Fig.2: ATV-5 after undocking on February 14th (Photo: NASA).

ATV-5 Airborne Observation Mission Goals:

During a three day workshop at the Institute of Space Systems in Stuttgart, Germany, in early March 2014, the observation campaign was sketched out and the scientific goals were defined. The campaign would set out to document the fragmentation sequence and identify the fragments through spectroscopy, characterize the explosive events through high spatial resolution imaging and spectroscopy, and track fragments for trajectory and footprint reconstructions against the star background.

The DC8 instrument suite was selected from about 40 different instruments with deployment heritage and evaluated against the three science goals. Spectroscopic instruments and hyperspectral imagers were used to spectroscopically characterize the explosive events and the identification of fragments. High speed cameras with framerates up to 20 kHz at high spatial resolution used in combination with low-light and intensified cameras were used in order to allow a thorough fragment tracking relative to the star background.

The airborne observation was part of a larger experimental consortium of ground and space based observations of this shallow re-entry. Observations from the

ISS would provide a second perspective for 3D trajectory reconstruction, while ground-based observations in the U.K., Australia and New Zealand would track the deceleration at high altitudes.

ATV-5 re-entry prediction:

The breakup of ATV-5 along its shallow re-entry path was simulated using the SCARAB software [1]. The model of a re-entry object in SCARAB primarily consists of a detailed 3D geometric model of the spacecraft with all external and internal subsystem components. Materials are assigned to each geometric element linking the geometry to a temperature dependent material database. Therefore, the geometric model is also a mass model with total mass, center of gravity and moments of inertia and serves as the physical basis for all destruction processes to be computed during re-entry. Secondary aspects such as temperature monitoring (e.g. glue weakening) or control functions (e.g. ignition of pyro devices) can be implemented if necessary.

The outer geometry is used to calculate aerodynamic forces and the aerothermodynamic heat loads and is modeled as a volume grid containing the mass data.

A SCARAB re-entry simulation starts from a defined initial state and the initial state vector was provided by ESA for the simulations of ATV-5. Six degrees of freedom equations of motion are solved deterministically with a Runge-Kutta integrator, automatic time step determination and error control. Aerodynamic forces and torques and aerothermodynamic heat loads are calculated at each time step for the current attitude and geometry. The attitude and geometry change constantly due to tumbling and melting and fragmentation respectively. All fragments are analyzed until either complete demise or ground impact. All ground impact fragments will be characterized by impact mass, velocity, size, shape and location. Based on the experience from the ATV-1 calculations, the criteria for fragmentation in the SCARAB simulation was set to 10% residual strength. This means that two fragments are generated when all connecting elements have reached a temperature at which only 10% of the nominal strength remains (at 300K).

The event of the first main explosion is assumed to be connected to the break up of the Propulsion Isolation Assembly (PIA), which is directly connected to the fuel tanks. This was a major result of the ATV-1 analysis and was considered to also hold true for the ATV-5 re-entry.

The SCARAB software was – among others - also used for a risk assessment for the shallow re-entry path. Fig. 3 shows an example for the predicted debris footprint for the re-entering ATV-5 in one of a number of possible reentry scenarios.

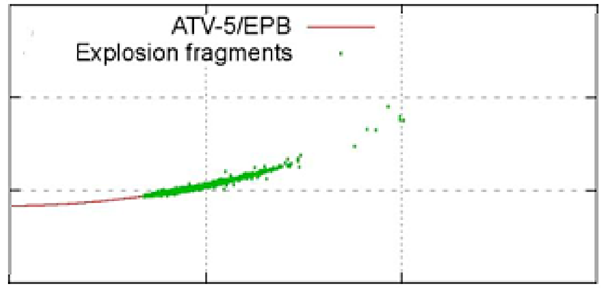

Fig. 3: Example of fragment footprint for as-flown ATV-5 from SCARAB

Using this data, a simulation of the observation was undertaken using an ESA tool called RENFOOT, which allows the simulation of the observation from a particular instrument depending on the instrument's parameters, the flight path of the aircraft, the trajectory of the spacecraft and the break-up scenario, provided here by SCARAB [5,6]. A main motivation for the development of RENFOOT was to analyse the Δv of fragments resulting from the explosions during the ATV-1 re-entry. The measured observation data from the ATV-1 re-entry was difficult to interpret, particularly in the first few seconds after an explosion, due to saturation and geometrical resolution. RENFOOT allowed the simulation of the observation instrument and from comparisons with measured data the unknown details could be resolved [8].

For the present investigation the fragmentation data provided by SCARAB was used for the trajectory data required by RENFOOT. An instrument with the capabilities of the RED system from Ron Dantowitz was used and the aircraft trajectory calculations provided by Jim Albers were used. The brightness of the fragments in RENFOOT uses three main sources, the radiation of the spacecraft's surface at high temperatures following a Planck curve, the shock radiation and the radiation of ablation products. The shock radiation contributes most of the measured signal but is not of particular interest for the fragmentation data. Therefore, it is not considered in the RENFOOT simulation, which means the simulated data is by far lower in signal intensity than the measured data, which includes the gas radiation of the shock layer around the fragments. The ablation of the material is considered in RENFOOT with a simple approach known from meteor calculations [9]. The signal received from a single fragment in a pixel of the CCD matrix is then the combination of both contributions, taking into account the distance to the object, the integration time, the camera aperture and the characteristic length of the fragment.

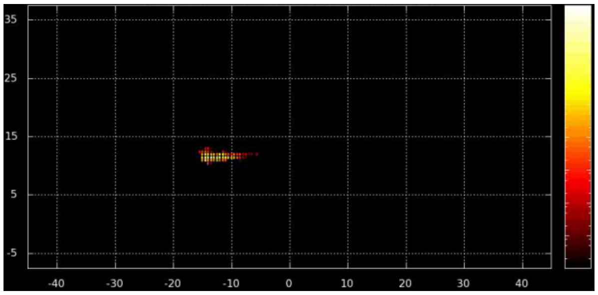

Fig. 4: Predicted manifestation of observed objects from a CCD camera aboard the DC-8.

Figure 4 shows an example of the rendering that was achieved after including the DC-8 orientation and bank profile during the reentry. Colors mark black body temperatures for the reentering debris.

DC-8 flight path:

The effect of the early solar panel breakup on the attitude of the ATV-5 vehicle during later parts of the entry was of interest, as it was the reason for the early explosive event seen in ATV-1. It was therefore chosen to place the DC-8 airborne platform close to the explosion point, but a little down range near the point where the breaking ATV would be (Fig. 5).

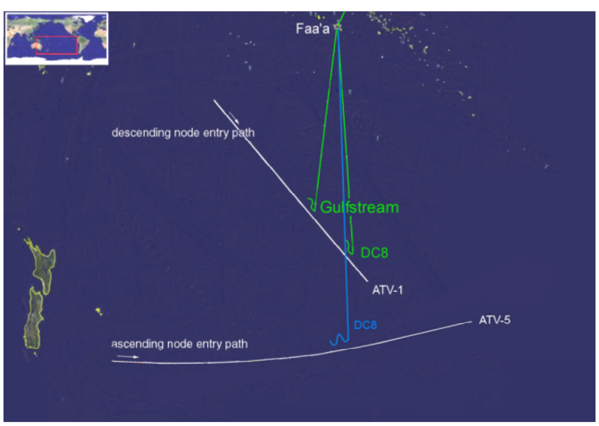

Fig. 5: Flight path and ground track of the re-entering ATV for ATV-1 and ATV-5 reentry observations.

This meant that the DC-8 had to execute a wider turn than during the ATV-1 "Jules Verne" Re-entry Observing Campaign to keep the vehicle in view of the observers at all times.

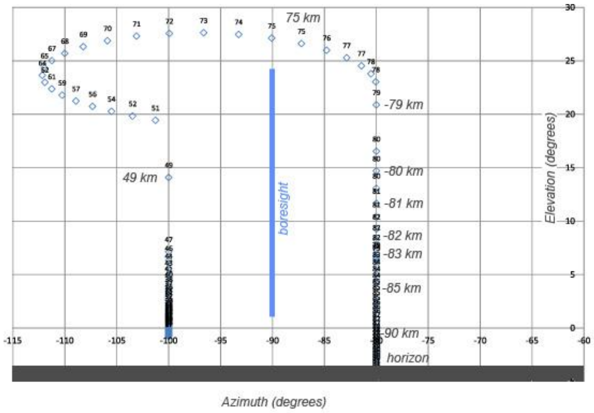

Fig. 6: Position of the ATV in the DC8 window frame relative to boresight. Angles are in azimuth and elevation.

A turn of increasing gradient was designed that would keep the ATV at constant azimuth 10º foreward from boresight until the DC-8 would reach the maximum safe turn angle of 15º. At that point, ATV would drift back in the field of view, passing by the DC-8 at highest angular velocity. By the time it's angular velocity slowed down and the DC-8 was able to catch up, ATV would be brought back to a position 10 degrees aft from boresight. Instruments in the front of the aircraft would have an unobstructed field of view of the early parts of the reentry low on the horizon, while instruments in the back would be able to follow fragments long after passing by the plane. All instruments would be setup so they could see the re-entry debris even if it would be at 30º elevation relative to boresight.

The RENFOOT simulations showed that this choice would put the explosion point at about the top of the constant azimuth leg, then cause an increasingly long debris train boresight of the window, with the front object lagging behind while the decelerated debris would stay nearly stationary in azimuth. Pending an uncertain altitude of the explosive event, this would maximize the viewing conditions.

Instruments aboard the DC-8:

The instrument suite foreseen for the observation is a trade-off between the scientific goals, possible redundancies and technological feasibility.

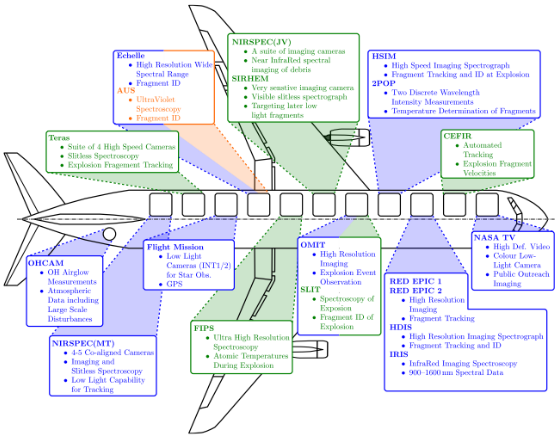

Fig. 7: Instruments aboard the DC-8 for the ATV-5 observation campaign.

Figure 7 provides an overview of the different instrument suites at the various optical window ports. For this mission, two new optical window ports were created in the DC-8 and two existing window ports were enlarged to accomodate existing large circular 16" diameter windows. Three extra instrument mounts were built to accomodate multiple cameras behind one optical window.

High and low spatial resolution imaging would be provided by NASA's TV imager (with regular HDTV output at standard sensitivity) and the SETI Institute's newly deployed highly sensitive Sony α7S digital video camera (both also used for near real-time video uplink to ATV-CC and the public), and by two co-aligned RED Epic cameras provided by Dexter Southfield School with a small (4º) and larger (15º) field of view and large pixel format CCDs [10].

Faint objects would be tracked by low-light Watec Wat 902H2 Ultimate cameras, set up as pointing cameras for most instruments, supplying a reference star-field for astrometry, and by a Xybion intensified camera contributed by Utah State University [11]. A staring intensified camera [12] would provide a fixed field of view that the aircraft pilot could use for environment awareness while turning during the entry.

Two long-focal length cameras were to focus on high spatial resolution events during the main fragmentation. Dexter Southfield contributed OMIT, the One-Meter Imaging Telescope, using an approach demonstrated in earlier missions [13]. New for the DC-8 was the deployment of the Coronograph for Explosion and Fragment Identification of Reentering spacecraft (CEFIR) instrument of Astos Solutions (Fig. 8), which would track ATV with a mirror gimble mounted against the wall of the aircraft with a custom-made mount [14].

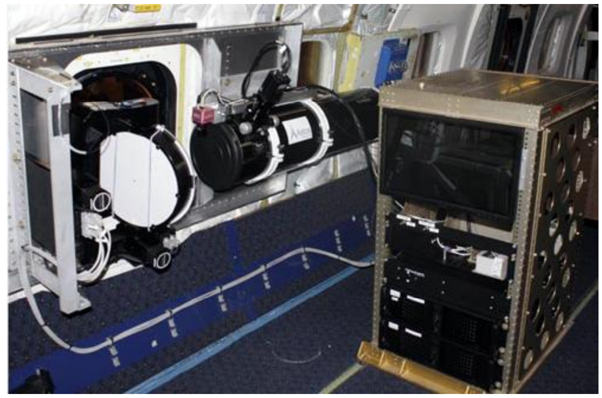

Fig. 8: The Coronograph for Explostion and Fragment Identification of Reentering spacecraft (CEFIR) instrument installed in the DC8.

High temporal resolution imaging at various spatial scales was to be performed by the TERAS and KAMELION high framerate cameras from the Technical University of Eindhoven [15]. Intensified high-framerate imaging was executed by the University of Alaska intensified ultrahigh framerate imaging spectrograph HSIM [16].

The Dexter Southfield 2POP instrument [10], would compare the brightness of point sources at two different wavelengths for temperature measurements, in order to differentiate low-T aluminum ablating components from high-T ablating titanium metals and other materials.

Slit-less spectroscopic observations of the fragments in visible wavelength range (400–880 nm) would be provided by a High Definition Visible Spectrograph (HDVS) [17] and a newly deployed Anastigmatic Hyperspectral Imager (AHI) of Dexter Southfield. Wide field fragment identification in the tail of the debris stream would be provided by the newly deployed SIRHEM spectrograph of the Observatoire de Paris IMCCE and by its NIRSJV slit-less near-IR spectrograph at 960–1600 . The Utah State University's NIRSPEC near-IR spectrograph would focus on the 960–1100 nm range at high spectral resolution to detect lines of carbon [18]. The slit-less Australian UV Spectrograph from the University of Southern Queensland would focus on spectroscopy in the 300–420 nm ultraviolet wavelength region for measurements of CN molecules and atomic lines [19].

Air plasma emissions from the main object leading up to the explosive event were targeted by the SETI Institute's high resolution ECHELLE spectrograph [20,21], and by the University of Stuttgart's SLIT instrument [22], the latter collecting light via a telescope and fiberoptic system and measuring with a newly deployed high resolution Echelle spectrograph Aryelle 150 from LTB Berlin. The University of Stuttgart also contributed FIPS [23], a Fabry-Perot spectrometer, designed to resolve the plasma emissions to measure the doppler motions in the emitting plasma in order to understand the mechanisms responsible for these emissions.

Figure 9 shows the wavelength coverage of the instrument suite and Fig. 10 the temporal resolution and the field of view of the instruments.

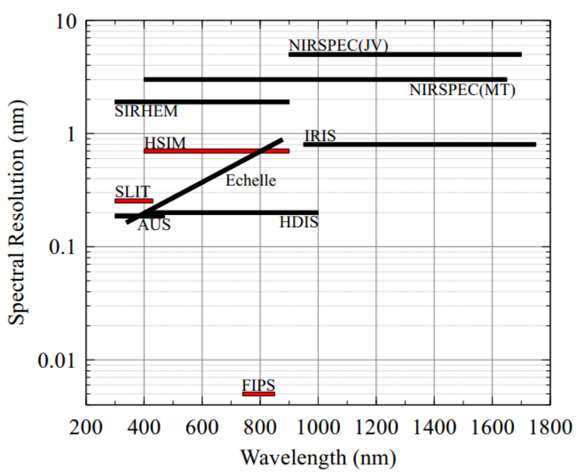

Fig. 9: Spectral resolution and wavelength coverage of the instrument suite (in red the instruments dedicated to the analysis of explosive events).

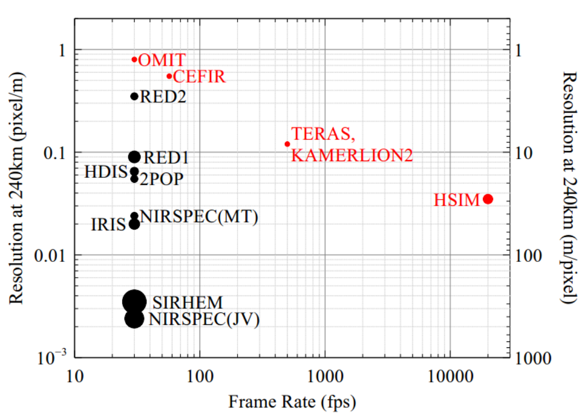

Fig. 10: Temporal resolution distribution of the instrument suite: The larger the spot the larger the field of view, the resolution is given for an object at 240km distance (in red the instruments dedicated to the analysis of explosive events).

In total a wavelength coverage from the UV (300 nm) to the IR (1700 nm) was reached at wavelength resolutions from 0.01 to 10 nm. The highest framerate were planned to measure the explosive events at very high temporal resolution in order to provide additional information of the Δv expected from the fragments. Therefore, a comparably small field of view was planned by OMIT and CEFIR taking the risk of a more challenging pointing requirement.

Figure 11 shows the floorplan of the DC-8. The positions of all instruments onboard the DC-8 are sketched. Compared to the past missions (ATV-1, Hayabusa), a new approach for the sharing of window space was chosen. The instruments are put together such that instruments with similar and compatible requirements are mounted on the same platform. Several new mounting platforms have been manufactured which allow a compact and standardized mounting of the instruments.

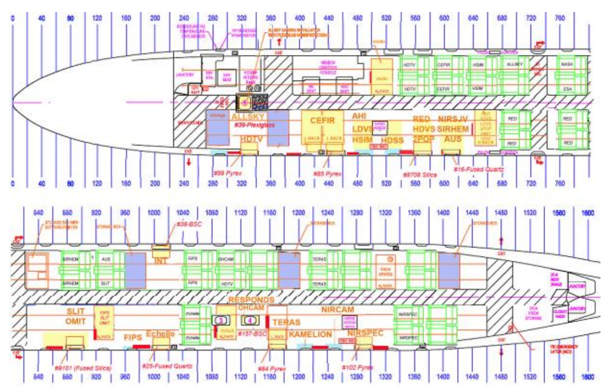

Fig. 11: Floorplan of the instruments as planned to be aligned aboard the DC-8.

The instruments are positioned with respect to the flown trajectory (see DC-8 flight path) and the measurement task as well as the space the instruments require. The instruments in the aft see the trail of fragments for a long time, therefore the intensified spectrometers for tracking and identification are positioned here. The explosion event characterizing instruments (OMIT, CEFIR) are put to the front.

Finally, in a new experiment, the OH airglow layer would be used to measure the explosive energy released in the pressure wave during the main fragmentation event. Embry Riddle Aeronautical University contributed two OH airglow imagers (OHCAM) in high elevation and zenith ports [24].

Validation data for the atmospheric wind models in the debris fall area would be collected by TWILIGHT, a newly developed Doppler wind lidar mounted in the belly of the DC-8 aircraft. Dropsondes would also be released for this purpose.

At the NASA Aircraft Operations Facility in Palmdale, instrument fit checks were performed using optical lamps mounted at the back of the aircraft hangar. Communication tests with ATV-CC were succesfully completed and video was uplinked through INMARSAT in near-real time. Figure 11 shows part of the science team in front of the DC-8 during the system fit checks. In addition, pressure checks and night time proficiency flights were successfully completed before the mission was ultimately canceled.

Fig. 11: Researchers (10 out of 31 person team) with the DC-8 aircraft at the Armstrong Aircraft Operations Facility, ready to deploy in a next opportunity. From left to right: R. Dantowitz (Dexter Southfield), F. Zander (U. Stuttgart), F. Fahlbush (Astos), T. Marynowski (U. Stuttgart), M. Kozubal (Dexter Southfield), S. Loehle (U. Stuttgart), P. Jenniskens (SETI Institute), S. Weikert (Astos), D. Buttsworth (U. Southern Queensland), and F. Gasdia (Embry Riddle Aeronautical University).

Summary:

This paper describes the preparation of the ATV-5 "Georges Lemaitre" Reentry Observation Campaign which was to conduct multi-instrument airborne observations of a controlled shallow reentry. Because ATV-5 could not execute its shallow reentry as planned, the observation campaign was not conducted to its very end. However, the need to understand the physics of shallow reentries remains. The preparations made for this mission and the tools developed to predict how the breakup will manifest to the observing teams can be directly applied to future controlled re-entries of ISS resupply spacecraft, be it reentries of the CYGNUS vehicle, Progress, or the HTV.

Acknowledgements: The ATV-5 "Georges Lemaitre" Reentry Observing Campaign was sponsored by ESA's Space Debris Office and the ESA International Space Station Program Office, by NASA's International Space Station Program Office and by the NASA Engineering Safety Council. Preparations for the mission were executed by NASA's Armstrong Aircraft Operations Facility.

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